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Top properties within the SM

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The high number of top quarks which will be produced at the LHC will allow precision measurements within the Standard Model. The weak decay of this very heavy particle is faster than QCD effects, which means that its properties can be deduced from its daughters without significant dilution. Measuring those properties, in a mass scale where new phenomena can be seen, is a natural way to probe the Standard Model and open windows on new physics. The CMS and ATLAS collaborations are actively preparing those studies. Some of them are presented here, with estimates of the accuracy that we can expect after one and more years of data taking at LHC.

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1. Introduction

The top quark observed at the TeVatron is compatible with the Standard Model (SM) weak-isospin partner of the b quark, which was expected to have a very large mass even before its discovery. However, present studies suffer from a lack of statistics, and they cannot rule out possible exotic properties of the top. Such anomalous behaviour is even predicted by some models, where the top plays a more fondamental role, particularly in the mass generation processes. Even if the top is nothing more than the sixth SM quark, discrepancies between observation and SM predictions in the top properties may be the sign of new particles and couplings unreachable at lower scales. Moreover, top processes may be important backgrounds for many analyses, such as some Higgs searches. Understanding the top quark properties and probing SM predictions is therefore a natural path towards new physics.
This will be possible at the Large Hadron Collider (LHC) under construction at CERN near Geneva. The startup of this proton-proton collider is expected in 2007. At initial luminosity ($10^{33} cm^{-2} s^{-1}$) it will produce in one year, with an integrated luminosity of 10 fb^{-1}, around 8 millions of $t\bar{t}$ pairs and 3 millions of single top events, in each of the general-purpose detectors CMS and ATLAS. Despite stringent cuts at trigger and analysis level, enough statistics will be available for precision studies of the top. Controlling systematic errors will thus be the crucial point for all top studies.

2. Event selection and reconstruction

Within the Standard Model, the top decays almost always into a b quark and a W boson, which decays itself into two light quarks or a charged lepton and its neutrino. Many top studies will look for the same signatures and thus use similar event selection criteria. For instance, when semileptonic $t\bar{t}$ pairs are used, the decay particles are qq$bl\nu b$ (Fig. 1). In this case, typical criteria are shown in table 1. They include trigger requirements, which in this case correspond to the isolated high-P_T lepton.
The reconstruction of the event also follows common paths. For semileptonic pairs, the hadronic W is retrieved by combining two light jets, which may be chosen among several ones: a typical criteria is to get the pair with invariant mass closest to well-known W mass. Information on leptonic W comes from the charged lepton and missing P_T which is associated to the neutrino: to get its longitudinal momentum, the lepton + neutrino pair is constrained by the W mass value. There is a

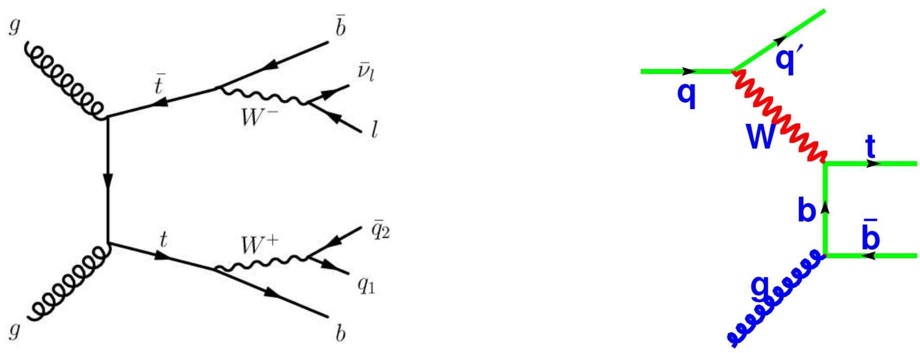

Figure 1: Left: semileptonic decay of a $t\bar{t}$ pair. Right: single top event through W-gluon fusion.

1 isolated lepton	$P_T > 20$ GeV	$\|\eta\| < 2.5$
($\geq$) 2 b-jets	$P_T > 30$ GeV	$\|\eta\| < 2.5$
($\geq$) 2 light jets	$P_T > 30$ GeV	$\|\eta\| < 2.5$
missing P_T	> 20 GeV	

Table 1: Typical selection cuts for $t\bar{t}$ semileptonic events.

twofold ambiguity in this calculation, which can be removed in various ways, for instance requiring the lowest P_Z value. The next step, which does not depend on the decay channel, is matching each of the Ws with a b. Tagging of jets which come from b quarks is therefore crucial for top studies. The best W/b matching method has to be determined in each study. For example, one may choose the Wb hadronic pair with mass closest to the top mass, then get among the remaining bs the one closest to charged lepton for the leptonic side.

3. Polarization studies

Polarization studies of a quark are usually difficult because of radiation and hadronization through QCD interactions. Those effects do not happen with top quark since its decay is faster (O(10^{-25}) s) than the QCD typical timescale (O(10^{-23}) s) [1]. Therefore, valuable information on the production and decay mechanisms of the top can be gathered through the study of polarization effects. It is thus possible to probe the 1/2 value of top spin and look for non-SM couplings, for instance a V+A component in the weak decay of the top, or a decay into a charged Higgs boson.
The work done in [2], [3] and, more recently, in [4] shows that the LHC can establish strong constraints on those phenomena. The aim of these studies is to determine the precision that one can expect, starting from 10 fb^{-1}, in the following measurements:

- helicity of the W coming from top decay;
- top polarization in single top samples;
- top polarization in top-antitop pairs, through asymmetries in pair production.

The top quark has three fermions in final state with almost no radiations, therefore the angular distribution of its decay products is directly related to its polarization P:

$$\frac{1}{N_{tot}}\frac{dN}{d\cos\theta_i} = \frac{1}{2}(1 + P\alpha_i \cos\theta_i)$$

θ_i is the angle between the chosen spin projection axis and the direction of flight of decay particle i, in the top rest frame. α_i is a coefficient between -1 and 1 corresponding to the spin analyzing power of the particle. Experimentally, polarization measurements are performed through angular distributions, and thus complete kinematic reconstruction of each top event is needed.

3.1 W helicity

Within the Standard Model, the polarization of the W^+ in top decay is divided in longitudinal, left-handed and right-handed parts according to the proportions in Table 2. The high percentage of longitudinal Ws is due to the high mass of the top quark; the V-A structure of the weak decay of the top forbids a right-handed helicity. Each of the three polarizations for the W boson leads

Longitudinal W^+: F_0	Left-handed W^+: F_L	Right-handed W^+: F_R
$\frac{M_t^2}{2M_W^2+M_t^2} = 0.703$	$\frac{2M_W^2}{2M_W^2+M_t^2} = 0.297$	0

Table 2: W^+ polarization in top decays. These are LO approximations, yet the proportions remain stable at NLO. The left-handed and right-handed components are reversed for W^-.

to a different angular distribution of the decay particles. The spin analyzing power of the charged lepton α_l is close to 1, therefore this measurement is performed in leptonic W decays. The lepton angular distribution in the Standard Model is:

$$\frac{1}{N_{tot}}\frac{dN}{d\cos\psi} = \frac{3}{2}(F_0(\frac{\sin\psi}{\sqrt{2}})^2 + F_L(\frac{1-\cos\psi}{2})^2 + F_R(\frac{1+\cos\psi}{2})^2)$$

ψ is the angle between the lepton direction in W rest frame and the W direction in top rest frame. The SM predictions for F_0, F_L and F_R yield the distribution of Figure 2. We illustrate

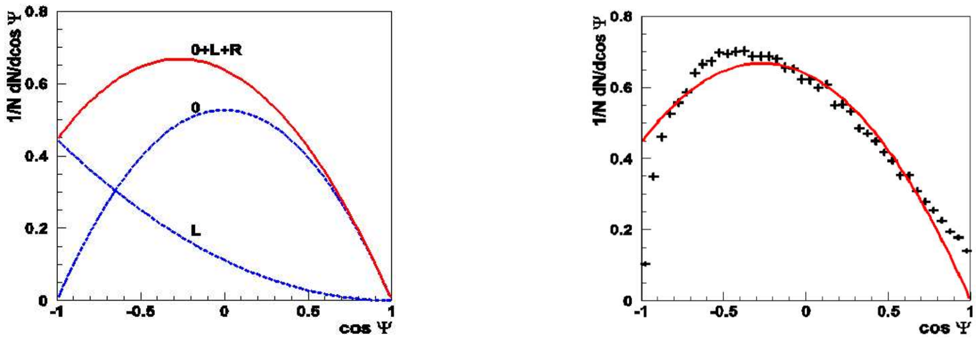

Figure 2: Left: angular distribution of lepton from W, for longitudinal (0) and left-handed (L) Ws, as well as their sum with SM proportions. No right-handed Ws (R) are expected. Right: W helicity in semileptonic $t\bar{t}$ events after reconstruction (dashed line). The expected distribution is reproduced (solid line).

the study of this distribution with [4], which uses Ws from top pairs processed through a fast simulation of the ATLAS detector. Each event is fully reconstructed with the criteria listed in section 2. Additional quality cuts are then performed to reduce combinatorial background from badly reconstructed events: the reconstructed hadronic W mass must be in a window of 20 GeV around the PDG value, and the hadronic and leptonic top masses must be in a window of 35 GeV around the generated value of 175 GeV. 85000 semileptonic (21000 dileptonic) events per year at low luminosity are selected, which corresponds to an efficiency of 3.3% (6.5%). The S/B ratio is around 12 for semileptonic and 6 for dileptonic events. The main background comes from $t\bar{t}$ events themselves, when at least one W decays into a tau (Table 3). The ψ angle can then be calculated;

	Expected events (10 fb^{-1})	$t\bar{t} \to \tau + X$	$W + 4$ jets	single top	other (sum)
$t\bar{t}$ semilep	85000	6200	[400,1000]	350	290
$t\bar{t}$ dilep	21000	3700	-	-	<350

Table 3: Signal and background for W helicity and spin correlation studies.

because of selection cuts and reconstruction effects, the distribution is quite different from the generated one (Fig. 2). This is due to the selection cuts and the effect of wrong particle choices and assignments. It can be corrected: the ratio between reconstructed and generated curves yields a fonction of $\cos\psi$ which contains all the distortion from the analyses. By applying this fonction to weigh each event, the bias is removed and the physics content from the reconstruction can be extracted. The resulting distributions and corresponding polarization values are shown in Fig. 3 and Table 4. Since the input SM polarization is retrieved, the method is unbiased and validated.

Full systematics studies were performed; the contribution of the most important parameters is

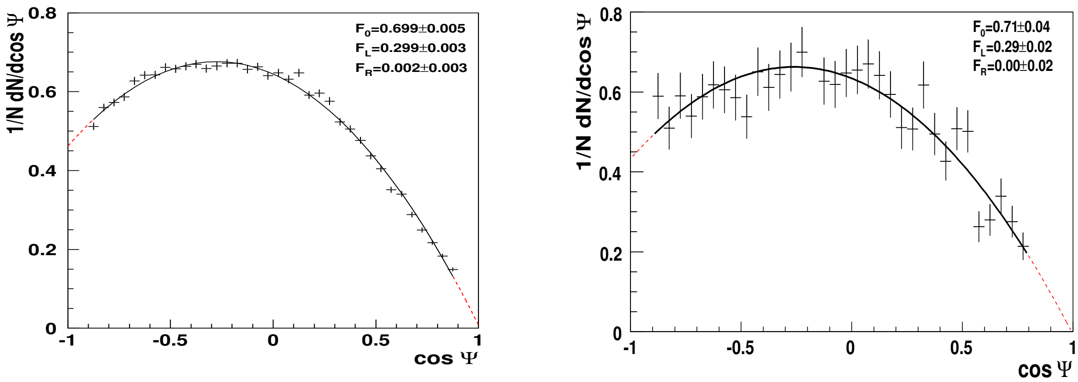

Figure 3: Corrected W helicity in semileptonic $t\bar{t}$ events after reconstruction. The events were processed through fast (left) and detailed (right) simulation of the detector.

	Fast simulation - $10fb^{-1}$	Full simulation - $0.5fb^{-1}$
F_0	0.699 ± 0.005	0.71 ± 0.04
F_L	0.299 ± 0.003	0.29 ± 0.02
F_R	0.002 ± 0.003	0.00 ± 0.02

Table 4: W helicity parameters extracted after reconstruction in the semileptonic channel, with statistical uncertainties.

Channel	Semileptonic		Dileptonic	
Source of uncertainty	F_0	F_R	F_0	F_R
FSR	0.007	0.002	0.008	0.008
Hadronization scheme	0.016	0.006	0.003	0.002
b-jet miscalibration (3%)	0.005	0.005	0.001	0.017
Input top mass (2 GeV)	0.011	0.004	0.007	0.014

Table 5: Main contributions to systematic uncertainties in W helicity measurements.

shown in Tab. 5. The results of the CMS and ATLAS analyses are summarized in Table 6. An overall 1 to 2 % precision can be reached with 10 fb^{-1} in the determination of the polarization parameters. The semileptonic decay channel yields the better contribution to this accuracy.

	F_0	F_R
Statistical uncertainty, CMS semileptonic	0.023	0.015
Systematic uncertainty, CMS semileptonic	0.043	0.053
Statistical uncertainty, ATLAS semi+dileptonic	0.004	0.003
Systematic uncertainty, ATLAS semi+dileptonic	0.015	0.024

Table 6: Expected uncertainties in W helicity studies with fast simulation for $10fb^{-1}$.

It is possible to deduce from this study the sensitivity that one can expect in the search for an anomalous tWb vertex. In a model-independent approach, an effective Lagrangian for this coupling can be defined, described by 4 parameters only [5]:

$$L = \frac{g}{\sqrt{2}} W_\mu b \gamma^\mu (f_1^L P_L + f_1^R P_R) t - \frac{g}{\sqrt{2}\Lambda} \partial_\nu W_\mu b \sigma^{\mu\nu} (f_2^L P_L + f_2^R P_R) t + h.c.$$

In the Standard Model, f_1^L is V_{tb} and the other couplings are equal to 0. Indirect constraints from B-factories and LEP have already set bounds on these 3 anomalous couplings. Using the W helicity measurement explained above, the bound on f_2^R, the less constrained of them, can be improved by a factor 3: a 2σ limit can be set on a value of $f_2^R = 0.04$.

The study of W helicity (and spin correlations in top pairs, cf. Section 3.3) are being performed using a detailed simulation of the ATLAS detector. Comparisons between fast and full simulation show good agreement, although they are limited by the moderate statistics of the very CPU-consuming full simulation production. Table 4 shows the current statistical uncertainty on full simulation data (around 120,000 signal events, corresponding to an integrated luminosity of 0.5 fb^{-1}). Update of relevant systematics studies is being prepared.

3.2 Single top polarization

In each single top production channel, a spin projection axis can be found where the top is almost fully polarized. The measurement of this polarization would be the first direct observation of the spin properties of a quark; it would also provide information on the production of the top. In [3] a study has been performed with tops from W-gluon fusion in fast simulation. In this channel, the top has a polarization above 90 % in the (nearly optimal) spectator quark basis, q' in Fig. 1. This polarization can be retrieved in leptonic decays, through the angle θ between the charged lepton in the top rest frame and the top direction in the center of mass of the incoming partons. Events are selected by requiring exactly one central ($|\eta| < 2.5$), isolated lepton with $P_T > 20$ GeV, one central b-jet with $P_T > 50$ GeV and one forward ($|\eta| > 2.5$) light jet with $P_T > 50$ GeV. The efficiency of the reconstruction is about 3 % and the S/B ratio is around 2.6. The reconstructed angular distribution contains a bias, specially at high negative $\cos\theta$ when the lepton and the top are back-to-back: the P_T of the lepton is then lowered by the top quark boost, and more events fail the selection criteria. The correct polarization can be calculated by using the following function:

$$\chi^2 = \sum_i \frac{(f_{th}(\cos\theta_i, P) + f_d(\cos\theta_i))^2}{\sigma_{th_i}^2 + \sigma_{d_i}^2}$$

f_d is a fit to the reconstructed distribution, while f_{th} is the expected curve when the polarization equals P. The value of P which minimizes the χ^2 is taken. The polarization value is 95.8 %, which is compatible with the parton-level value of 94.6 %. The uncertainty expected with 10 fb^{-1} is around 1.6%, which includes statistical errors and systematics due to a variation of background of $\pm 20\%$.

3.3 Spin correlation in top pairs

Each of the tops in a QCD-produced pair is not polarized. However, the production of like-spin pairs is more abundant than unlike-spin ones at the LHC, for low values of the $t\bar{t}$ invariant mass (Fig. 4). This can be expressed as an asymmetry using the following variables:

$$A = \frac{\sigma(\uparrow\uparrow)+\sigma(\downarrow\downarrow)-\sigma(\uparrow\downarrow)-\sigma(\downarrow\uparrow)}{\sigma(\uparrow\uparrow)+\sigma(\downarrow\downarrow)+\sigma(\uparrow\downarrow)+\sigma(\downarrow\uparrow)} = 0.33 \ (0.42 \text{ if } M_{t\bar{t}} < 550GeV)$$

$$A_D = A_X + A_Y + A_Z = -0.24 \ (-0.29 \text{ if } M_{t\bar{t}} < 550GeV)$$

The expected SM values are indicated in each case. The asymmetries can be improved by rejecting pairs with invariant mass above an arbitrary threshold. Values with a cut at 550 GeV are shown.
Measurement of this asymmetry would probe the production of top pairs. This asymmetry can be observed through a correlation between the angles of the decay particles coming from the tops. Two kinds of angles can be defined: the θ_1, θ_2 angles between the top (resp. antitop) and its decay product, in the top rest frame; and the Φ angle directly between decay particles from each top in their respective top rest frames. The asymmetry variables appear in those angular distributions:

$$\frac{1}{N_{tot}} \frac{d^2N}{d\cos\theta_1 d\cos\theta_2} = \frac{1}{4}(1 - A\alpha_1\alpha_2\cos\theta_1\cos\theta_2)$$

$$\frac{1}{N_{tot}} \frac{dN}{d\cos\Phi} = \frac{1}{2}(1 - A_D\alpha_1\alpha_2\cos\Phi)$$

The charged lepton is optimal because of its high α, but in the hadronic side of the semileptonic channel one quark has to be used. The best spin analyzing power is obtained by choosing the non-b jet with lower energy. In [4] full reconstruction of the event is performed, and the same quality cuts as in Section 3.1 are applied. With the additional cut on the $t\bar{t}$ invariant mass of 550 GeV, the efficiency of the reconstruction is 2.3 %. An event weighting procedure similar to the one described in Section 3.1 is applied to correct biases on angular distributions. The same systematics

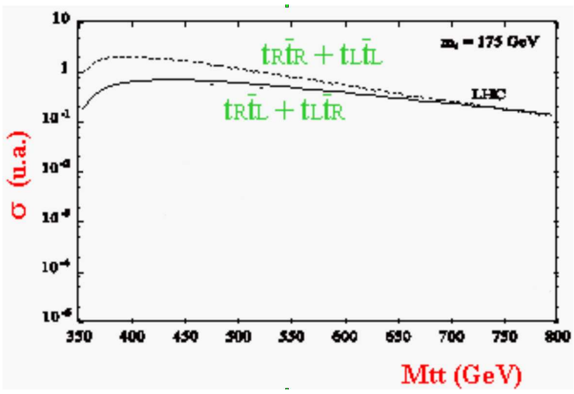

Figure 4: Production cross-section for $t\bar{t}$ pairs at the LHC, with same (dashed) and opposite (solid) helicity.

study as in W helicity study was performed, and for spin correlations the main contributions to the uncertainties come from parton density functions, the b quark fragmentation, miscalibration of b-jet energy and the top mass value. The final results are summarized in Table 7. A precision of a few % can be expected after one year at low luminosity, an order of magnitude better than present values.

	$\frac{\Delta A}{A}$	$\frac{\Delta A_D}{A_D}$
Statistical uncertainty, CMS dileptonic	11 %	-
Systematic uncertainty, CMS dileptonic	9 %	-
Statistical uncertainty, ATLAS semi+dileptonic	3 %	3 %
Systematic uncertainty, ATLAS semi+dileptonic	6 %	3 %

Table 7: Expected uncertainties in $t\bar{t}$ spin correlation studies with fast simulation for $10fb^{-1}$.

4. Top charge

Standard Model $t\bar{t}$ pairs decay into $(W^+b)(W^-\bar{b})$. However, a pair of exotic tops with an absolute electric charge of 4/3 would have the same final state, but with a different matching: $(W^+\bar{b})(W^-b)$. Specific top charge measurements are therefore required to rule out or confirm this exotic value, which is predicted by some models (in this case the actual top quark is heavier and has not yet been observed). To measure the top charge two methods have been proposed [6]: study of radiative $t\bar{t}$ processes; and charge measurement of decay particles. The first method consists in cross section measurements of $t\bar{t}$ pairs where a photon is radiated, either at the production or the decay of the pair. This radiation depends on the value of the quark charge; yet the distinction between SM and exotic charges may require many years of data taking.
Faster results could be obtained with charge measurement of decay particles, namely a W boson and a b quark. The W charge in leptonic decays is accurately given by the lepton coming from it; the b charge is more challenging. The b quark initiates a jet, whose charge can be estimated by a weighted sum of the charges of the particles in the jet, as in the following formula:

$$Q_{b\,jet} = \frac{\Sigma_i q_i |\overrightarrow{j} \cdot \overrightarrow{p_i}|^\kappa}{\Sigma_i |\overrightarrow{j} \cdot \overrightarrow{p_i}|^\kappa}$$

$\overrightarrow{j}$ is the direction of the jet, and q_i and $\overrightarrow{p_i}$ are the charge and direction of particle i in the jet. Coefficient κ has to be tuned to get the best estimate. A correct W/b matching is necessary to get the right top charge. The matching criteria chosen use the invariant mass of the lepton+b pair, compared to the top mass. An invariant mass above 175 GeV implies that the matching is not correct; therefore, by requiring that the chosen matchings are below this mass and other matchings are above, a high purity can be achieved. Those criteria imply low efficiencies, specially in the semileptonic channel, but the S/B ratio is high (10 for dileptonic and 65 for semileptonic). The measured value of the charge is around -0.11 (0.11) for b-jets ($\bar{b}$-jets) with a statistical error of 0.002 for 10 fb^{-1}. Good accuracy in the separation between b and $\bar{b}$ charge distributions should therefore be achieved. Systematics have to be estimated in this study.

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5. V_{tb} matrix element

The CKM matrix element V_{tb} is expected to be very close to one, which leads in particular to the privileged decay of the top into Wb. Verification of this value would be another confirmation of the three-generation structure of fermions; deviations from SM could point out exotic top decays. This measurement cannot be directly done in $t\bar{t}$ pairs; only the ratio: $(|V_{tb}|^2)/(|V_{td}|^2+|V_{ts}|^2+|V_{tb}|^2)$ can be calculated. Electroweak single top events allow direct measurement because their cross-sections are proportional to $|V_{tb}|^2$. Some ATLAS studies [7] have been performed in s-channel and W-gluon fusion. Their accuracy estimate for V_{tb}, around 5% relative error in both cases, was largely dominated by the theoretical uncertainty on the cross-sections. Recent calculations [8] have improved those uncertainties, which should lead to lower uncertainties on V_{tb}.

6. Top Yukawa coupling to Higgs boson

If the SM Electroweak symmetry breaking mechanism is confirmed by the discovery of the Higgs boson, a very good place to study its Yukawa couplings to fermions is the top quark, because of its high mass. In this case the coupling is close to one, an intriguing fact which could be due to a more fundamental role of the top in the Electroweak symmmetry breaking mechanism. The associated production $t\bar{t}$H is one of the privileged channels for observing the Higgs boson and it allows direct measurement of the top Yukawa coupling. However, the total Higgs width cannot be measured at the LHC, because some decays will not be accessible, in particular H to two gluons. Thus a theoretical assumption has to be made for the unreachable channels in order to extract the absolute coupling. The ratio of couplings, for instance $g(t,H)/g(t,W)$, does not need those hypotheses, and it can be measured in combination with other Higgs channels. A study [9] has been made using all current Higgs analyses in ATLAS, to estimate the errors in the measurement of relative and absolute couplings. These measurements will require much statistics and will probably not be significant before nominal high luminosity of the LHC ($10^{34}cm^{-2}s^{-1}$). Figure 5 is a summary of the relative precision expected on each coupling (absolute and relative), as a function of the Higgs mass. The errors which can be achieved are of the order of 20 to 30 % for the top coupling after three years at high luminosity.

7. Conclusion

The LHC offers many possibilities to make precise measurements of the top properties. A one to five percent-level precision on W helicity and top spin measurements can be reached after one year of data taking at low luminosity. Measurement of top charge also seems feasible after one year. Measurement of V_{tb}, which depends on single top studies, should be done with an accuracy better than 5 %. At a longer timescale, the Yukawa coupling to the Higgs boson could be measured with a precision of some tens of percent. The combination of those measurements will confirm the validity of the SM at the 100-GeV scale, and maybe point out new phenomena. The next few years before LHC first runs will be useful to improve the understanding of systematic uncertainties in all those top precision studies.

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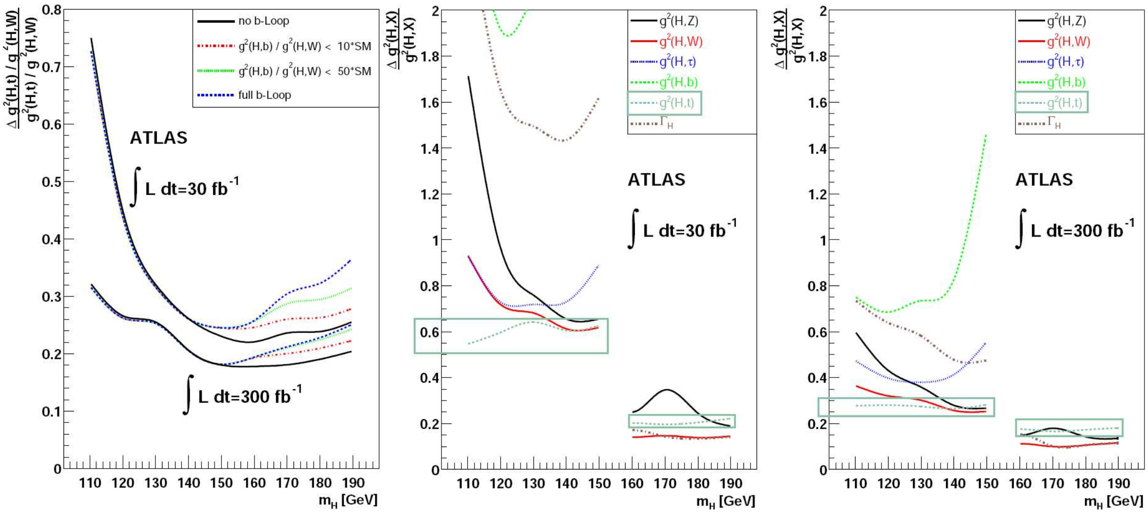

Figure 5: Relative accuracy on Higgs couplings measurements. Left: ratio of coupling to top over coupling to W. Right: absolute couplings; theoretical assumptions are different below and above 150 GeV.

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